Mu2e Tracker Straw Tensioning

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SIST Program 2013

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August 8, 2013

Contents

1 Abstract

Mu2e is a project at Fermilab that looks to observe the conversion of muons wholly into electrons. This differs from the normal decay path of an electron with less mass and two neutrinos. In doing so they have devised an accelerator to view as many muons interactions as possible.

In order for their experiment to go correctly the detection mechanisms must be working properly. The tracker is a device that records the momenta and trajectory of muons passing through it. This process is done by a portion of the trackers known as drift chambers.

The drift chambers are composed of an outside straw filled with ionized gas and an inside wire. The outside straw is held at ground while the inside wire is held at a high voltage. When a muon passes through the gas is ionized and the wire collects the negatively charged particles as a signal.

In order for the drift chambers to work the wire must be centered with respect to the straw. This means that the straw must be tensioned to avoid any sags while it is in the detector. Using the resonant frequency-tension relationship for a string as inspiration, this paper covers the process by which the relationship of resonant frequency, length, and tension were discovered for the straw

2 Introduction

Mu2e is a project at Fermilab that looks to observe the conversion of muons wholly into electrons. This differs from the normal decay path of an electron with less mass and two neutrinos. The process by which they plan to achieve this is by having a proton beam source strike a water-cooled aluminum target. This will create a cascade of particles including pions that decay into muons. The muons will then be concentrated into the detector solenoid. In this detector there is the Tracker and the Calorimeter that collect redundant information regarding the particles energies and momenta. [1]

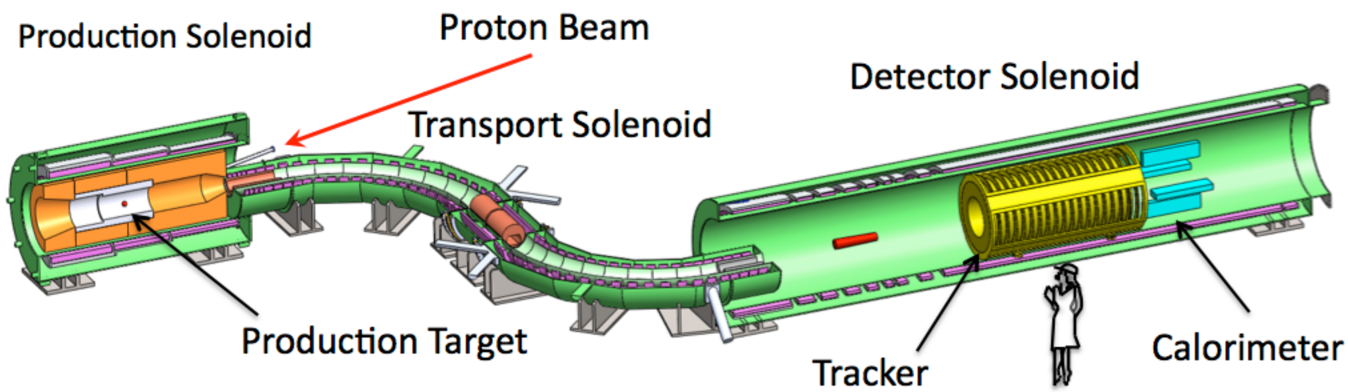

Figure 1: Mu2e schematic

In Figure 2 the tracker is shown in more detail. The red sections are what are known as drift chambers. These drift chambers are comprised of two parts the outside straw and the inside sensing wire. How these work are that the straws are filled with a gas that ionizes as a muons enters the chamber. The straw is held at ground potential and the sensing wire is held at a high voltage. This forms an electric field similar to a capacitor and the negatively charged particles are attracted to the sensing wire which then sends a signal which is used to identify all relevant information. The primary concern with this setup is that if the sensing wire is not directly centered with respect to the straw any static build-up may cause the wire to be attracted and cling to the inside of the wall shorting out the wire. Therefore both the wire and the straw must be tensioned in order to guarantee the wire is centered. It has been determined that the straw must be tensioned to two newtons in order to insure straightness. Taking into account drift affects over the five years of Mu2e's operation and they must be tensioned to seven newtons. This means that I must be precise in our tensioning.

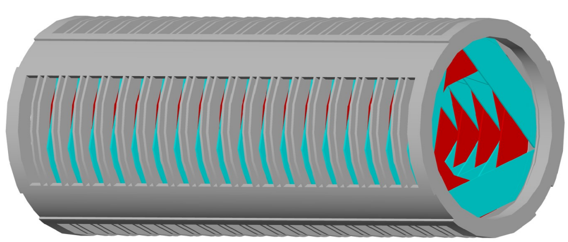

Figure 2: Mu2e tracker

[1]If interested one can visit `mu2e.fnal.gov/how_does_it_work.shtml`for complete information regarding how Mu2e is planned to be carried out.

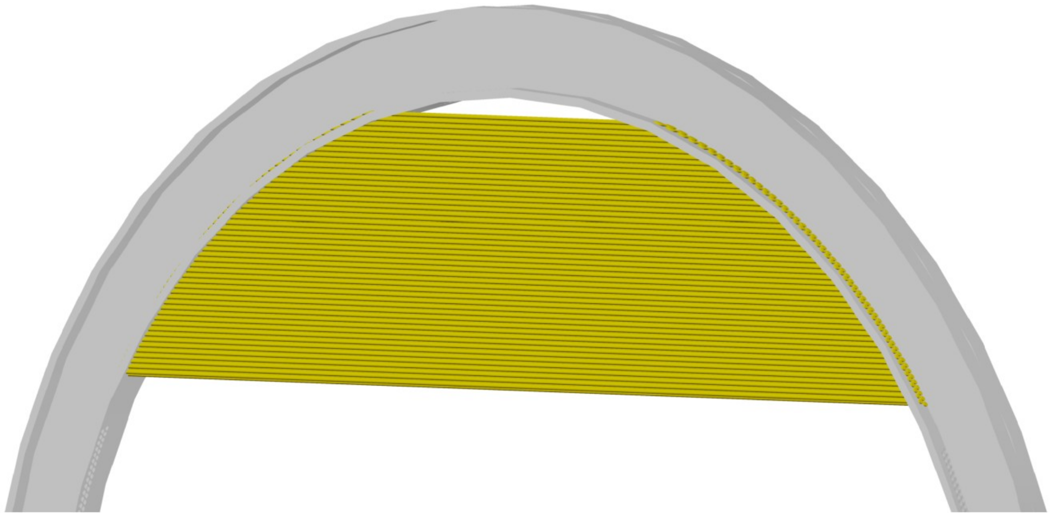

Figure 3: Straws on gas manifold

In tensioning the straws the first step must be to determine the tension of the straws at any moment. The approach that I have taken in doing this can be easily understood by using frequency to tension relationships for a string. I will first explain in this context and then return to our straw.

A useful illustration for understanding the vibrations of a fixed string is to consider a guitar. A guitar string, like our straws, can be considered homogeneous, of constant length, of constant tension, and having fixed ends. When someone plucks the string it begins to vibrate. Since one cannot force the string into a perfect sine wave by plucking it, you give the string a travelling wave that can be decomposed into many different frequencies using Fourier analysis. Since no pluck is identical you may draw the conclusion that different sounds will be made each time, but any exposure to a guitar quickly rules that out. What is happening is that while you do excite many frequencies you will always excite the resonant frequency of the string. The amplitude of this frequency is the highest and therefore contributes the most to the overall construction of the wave. This means that the resonant frequency determines the note and insures the consistency one expects.

So with the above paragraph in mind how does one describe the change in pitch when you tune a guitar or place your finger on a fret? In order to account for this the resonant frequency must change with both the tension(due to tuning) and length(placing your finger on the fret).

This description of the string ,while useful, is purely qualitative. With this understanding we can observe the frequency-tension relationship that has been observed for a string.

$$f_1 = \frac{\sqrt{\frac{T}{\rho}}}{2L} \tag{1}$$

f_1 = Resonant frequency
T = Tension
L = Length
ρ = Mass density

I have shown the relationship for a string so why is this model not good for the straw in discussion? The straw deviates from the string by two means. One is the mass of the straw is concentrated to a thin layer whereas the string's mass is distributed along a line. The other is that for an ideal string there are infinite degrees of freedom, this is just not true for our straw as it has noticeable rigidity. So we cannot use the string equation and a relationship must be found. And thus is the purpose of this document.

3 Concepts and Hardware

If we wish to follow the example of the string and assume that there is an understandable relationship between tension and frequency, we must first choose the variables we wish to control. The most obvious one is to control the length. This can be done by stringing the straw up similar to a guitar as shown in 4. Also while the straw's mass density is not linear it is constant. However further analysis of this system shows that there is no easy way to measure the frequency or determine at what tension you have the straw at and therefore must be revised. An additional problem is that while we are able to pluck the straw mechanically during the research and development process, we will not be able to do this in practice as the straws have a separation of 1mm.

In order to overcome this problems I have a devised a new system. This is shown in Figure 5. We have added three additional components being the battery, a magnetic field, and a pulley. First the battery and the magnetic field together work as the excitation mechanism. Since the straw is a conductor if you connect a battery you create a flow of current. Placing the straw then in a magnetic field forces the straw upward, at least in the configuration shown. If the battery is then turned off the straw will oscillate as it returns to its equilibrium position. Second the pulley is added as a way to place a hanging mass to accurately tension the straw.

The realization of this method is shown in Figure 6. The battery is connected by pins that are permanently in contact with the straw and the magnet is placed in the center of the straw in order to excite primarily the odd harmonics. The pulley, that is not shown, is ran through the block at the end to insure it pulls straight. One may argue that the length of the straw at different tensions now varies, but with such small amplitudes of oscillations the assumption is that the pins will in fact determine the length of the straw. This however does come with its own drawbacks. When tensioning the pins now introduce friction which reduces the tension applied to the straw. Also since the straw is stretched the effective mass density changes with tension. These changes are however assumed to be minimal.

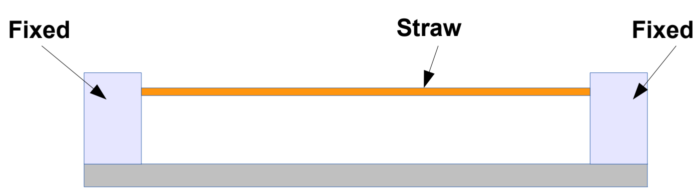

Figure 4: Straw setup

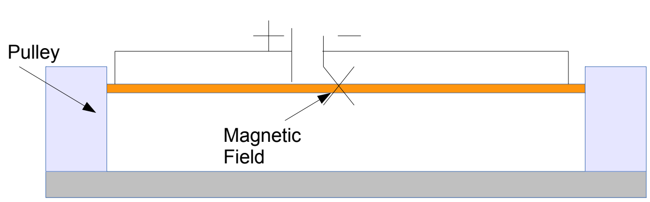

Figure 5: Final setup

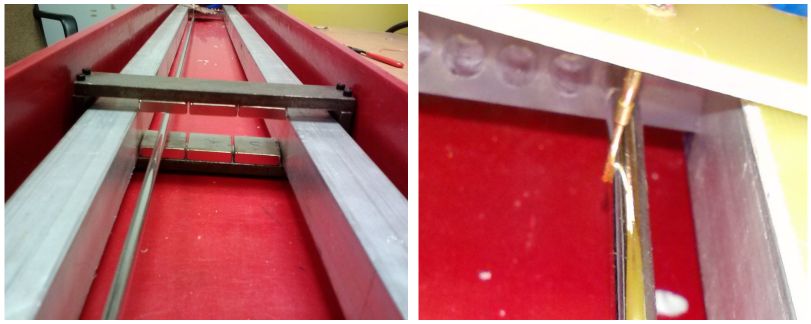

Figure 6: First realization

The beauty of this configuration is not truly apparent until you realize the methodology by which the frequency can be measured. If you consider that after the straw has been plucked it is oscillating in a magnetic field you must draw the conclusion that an emf is produced with exactly the same frequency of the oscillations. While this emf is of the order of microvolts if one amplifies this by an order of a thousand you could observe and record the results.

After the general idea of how we plan to do this was in place we considered more technical details. The first of which was to make a board that does the switching of the battery on and off and the recording of the emf data. The board that was originally constructed can be seen in Figure 7. The way that this worked is that the left-most switch is turned on and current is allowed to flow through the 220 ohm resistor that is representative of the straw. This switch is then closed and after a short delay the second switch is opened and the emf of the oscillating straw is used as the input to the non-inverting configuration.

In Figure 7 you can see that some of the leads are marked "to Arduino". The Arduino Due was the microcontroller of choice to use for the switching and processing of the data. The reason that this was chosen was the plug-and-play nature of the Arduino. It is open source and therefore has many pre-written libraries that are available. The Due sports a 12-bit ADC with a reference voltage of 3.3 V. This allows us to see a precision of 0.8 mV per division which leaves very little ambiguity in its results. The Arduino's ADC does require a biasing network in order to measure sinusoidal signals as it cannot go negative. The values of resistance were chosen to come as close to halfway of 3.3 V using stock resistances. This came to 1.8 V which means that we can observe a sign wave of 1.5 V magnitude limited on the positive side.

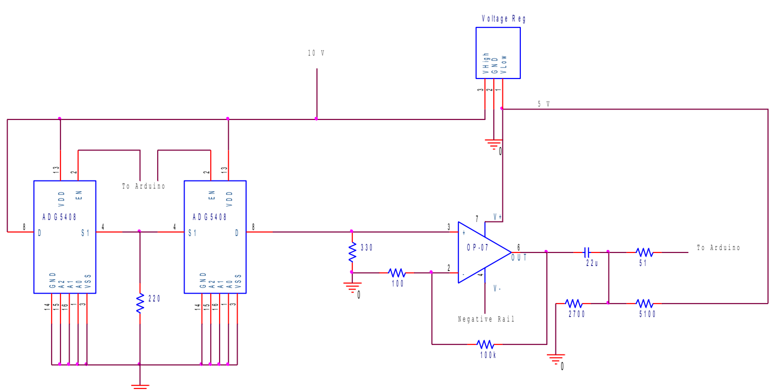

Figure 7: Circuit

4 Measurements and Data Acquisition

After the hardware had been chosen I had to determine the best method by which to acquire data and conduct an analysis.

The first hurdle that was to be overcome was processing the data coming into the ADC. An example of this data is shown in 8. The top graph represents the readout of the ADC against reads of the Arduino(time would actually be the x-axis times the clock cycle). The clock cycle shown here is .38 ms. The bottom graph is a plot of the FFT of the original signal. Also keep in mind that since the period is .776 s this is normalized hertz. For example Figure 8's first harmonic would actually be 80 / .776 = 103.09 Hz from Eq. 2.

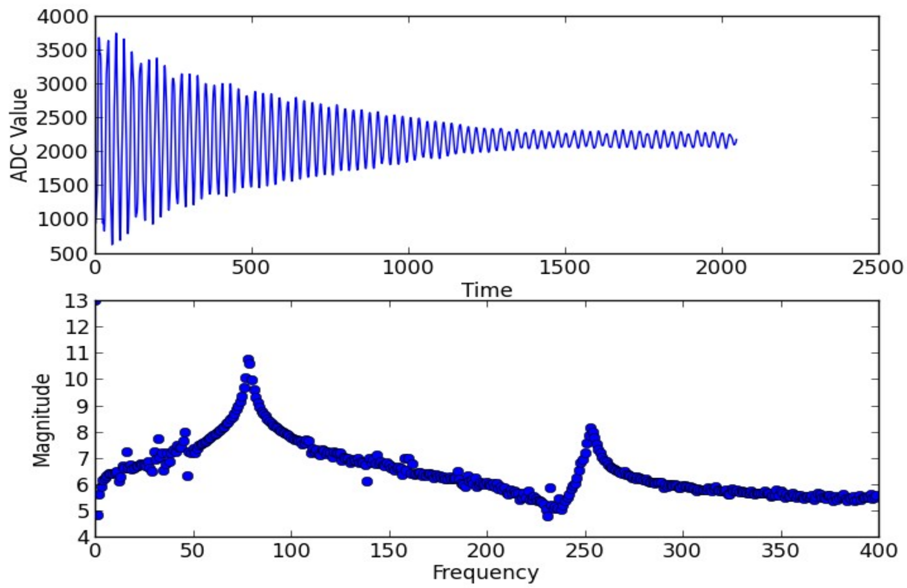

Figure 8: Circuit

As with any measurement you want the precision to be the best that you can possibly get. Originally I thought the more points you have and therefore the higher the sampling rate the better precision can be acquired. This is not true.[2] In order to have a better precision you want the value of f_D to be as small as possible. If I multiply both sides of Eq. 2 by f_S you can see that samples cancel out. This leaves the only possible value you can change is seconds so taking data for longer increases your precision. As you can see from Figure 8 the magnitude of the oscillation is quite low when I stop taking measurements and going further may mean it is indistinguishable from noise. With this in mind the time of .776 s is the longest period that I am comfortable in taking and our precision is 1 / .776 = 1.3 Hz.

$$f_D = \frac{f_A}{f_S} \tag{2}$$

$$f_D = \text{Digital frequency } \frac{Cycles}{Sample}$$
$$f_A = \text{Analog frequency } \frac{Cycles}{s}$$
$$f_S = \text{Sampling frequency } \frac{Samples}{s}$$

[2]You must of course be able to reconstruct the signal and therefore the sampling rate must be at least twice the frequency you wish to observe as stated by Nyquist's theorem.

This process was all originally done by sending the ADC readouts to the computer to be processed using Python code. However using the ARM math library we were able to use Ardruino exclusively for computation and therefore eliminate the need for a computer altogether.

Of utmost importance with any measurement is being able to determine the level of noise present in your measurement. There are three noises two of them being readily apparent and one not so much. The first two are mechanical and electrical. The mechanical consists of both air currents in the rooms and vibrations of the beam mount and the table it rests on. The electrical is your normal electrical noise from operating a circuit such as resistors thermal noise. The third and less apparent noise was an electromagnetic radiation. This occurs because the straw acts as an antenna and is a very interesting case.

If you look closely at Figure 10 you can notice that the noise has a peak at roughly 48 Hz. This was first observed to occur in our measurements and then shown to happen even when the straw was not excited. If normalized this comes out to approximately 60 Hz. This was the first indication that it had to do with something power line related. The next thing I did was remove the straw and this noise was not observed. After I placed an alligator-alligator clip from the input of the op-amp to ground. When this happens the frequency reappears and you can adjust the amplitude by changing both the orientation of the loop and the size of the loop. This verifies that this is an em radiation that is causing our frequency. This radiation is from machines in the facility operating at 60 Hz. If moved to another facility this radiation may not be present.

In my effort to reduce noise I came up with the configuration shown in Figure 9. What has changed is that the bar is double-sided sticky taped to the table and clamped on both ends. The straw is then covered with an aluminum cage that acts as a Faraday cage. Finally the cage is covered s with the styrofoam box to eliminate any flow of air currents.

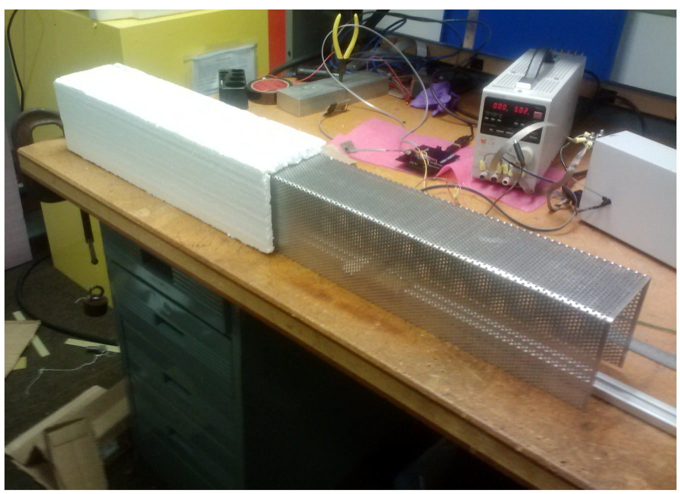

Figure 9: Noise reduction

Our conclusion is that the noise is about 40 divisions peak-to-peak and since our signal reaches a minimum of around 200 peak-to-peak we are safe in taking those measurements. However since this means the noise to signal ratio is 1/5 at the end. This is definitely the longest that we can take our signal.

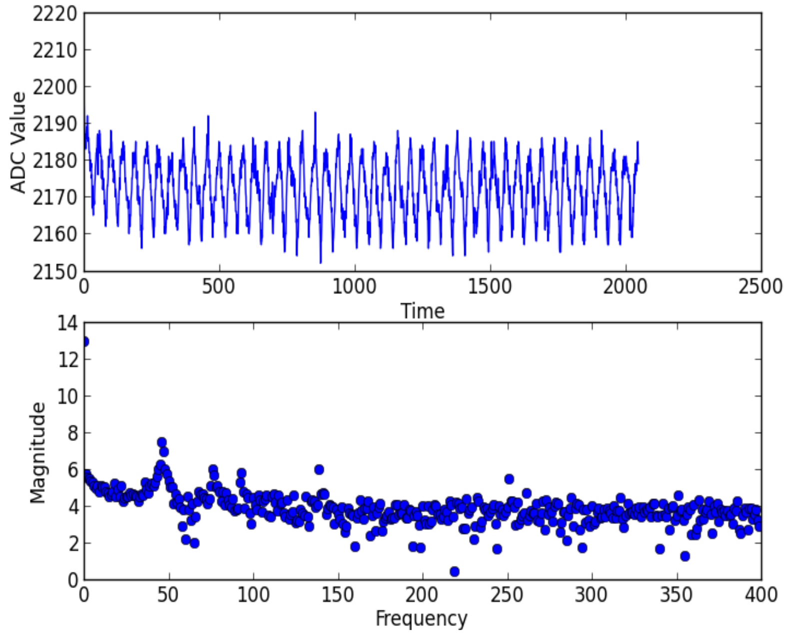

Figure 10: Noise

With the noise and method of data acquisition understood the next thing needed to be understood is the peak-finding algorithm. This is used to properly determine the frequency from the Fourier spectrum. I attempted three methods in doing so the maximum method, average method, and curve fitting method. Each method is described below and Figures 11 shows histograms for 1000 sets of data for each method.

Before I explain each method it must be stated that this was done around the third harmonic instead of the first. The reason that this was done was to decrease our percent error. This is valid as a measurement of the third harmonic in essence is just a measurement of the first scaled by three. Therefore the error is as well scaled by three and for a constant error of +-1 it can be reduced to +- 1/3.

The max method is the simplest method and forms the foundations for all of the methods. The idea is find the maximum value in the y axis, other than the dc value, and call it the first harmonic. Then multiply that by three and put a range of +5 and -5 to find the peak in that area. This maximum is the third harmonic. In Figure 11 it can be seen that most the time it is consistent at 107 but sometimes you can get as low as 104. Meaning you can go as far down as -3.

The next method is the average method. This is conducted by first using the maximum method and then taking two points on each side and conducting a weighted mean. The average histogram in Figure 11 shows a much nicer distribution that is approaching Gaussian with a width of +-0.2.

The last method conducted was the curve fitting method. This starts identical to the maximum method and then fits a curve around the third harmonic. This was done using Python package numpy's curvefit command. Apart from giving errors quite often it also give a worst distribution than the average method.

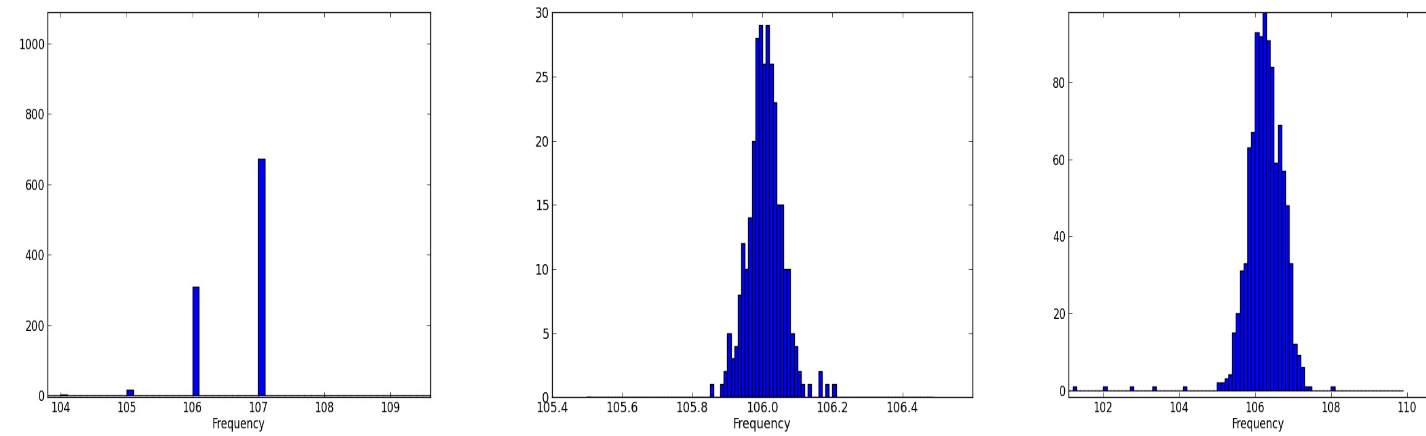

Figure 11: Max, Average, Curve Fitting

The decision was then made that the average method provided the most consistency and data was taken over the weekend. Figure 12 shows this data. The interesting part about this data is that there are actually three distributions the primaray one at 106, a smaller one at 107, and an almost non-existent one at 105. The first distribution has a width of +-0.2 so that is what we expected to get from our average algorithm. When looking at the saved data from over the weekend it shows that the 107 frequency does not occur till Monday morning a few hours prior to my arrival. This leads me to believe that this may not be an error in our measurement but vibrations introduced from machinery that was turned on by the technicians. The 105 seemed to be distributed throughout the measurements and may be faulty readings but I did not find an exact reason for them. Even taking the error to be +- 1 including all three distributions it still is better than the curve-fitting method as it removed all outliers.

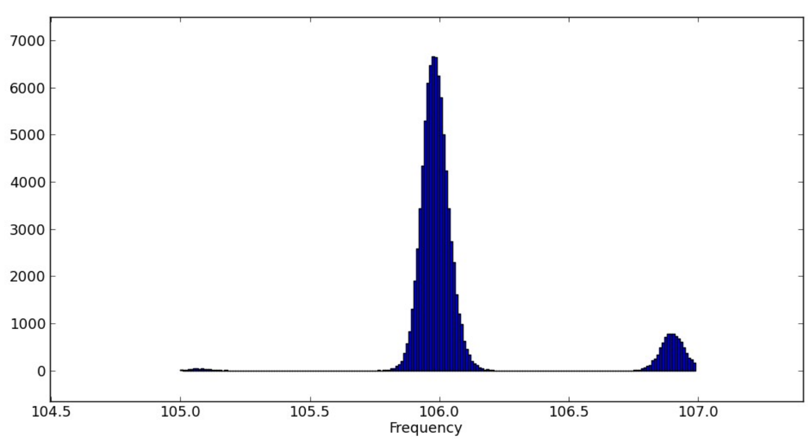

Figure 12: Weekend data

The last consideration was the dependence on pressure, humidity, and temperature. The temperature and the pressure in the lab remained relatively constant and looking over the small ranges that we have shows no change in the measured frequencies. Humidity however is a completely different story.

In Figure 13 the plot of Frequency vs. Humidity is shown. This is at a set hanging mass of 500g. This data has been fitted and a correction for frequencies can be made. This data however is far from complete as the straws are to be installed in an environment of 20% relative humidity.

Figure 13: Frequency vs. Humidity

5 Results

After the methods and hardware were all determined measurements were taken over two lengths of straw being 124.5 cm and 63.5 cm. Two trials were conducted for each straw. These were taken over a range of 500g - 800g. The slopes of the longer straws are Red = 8.65x + 64.13 and Blue = 8.68x + 64.05. The slopes of the shorter straws are Red = 16.85x + 167.76 and Blue = 16.87x + 166.72. What can be seen is that frequency is directly proportional to the tension and the frequency is inversely proportional to the length. The frequency does however experience approximately a constant 40 Hz offset. These measurements were conducted in short periods of time so changes in humidity can be neglected.

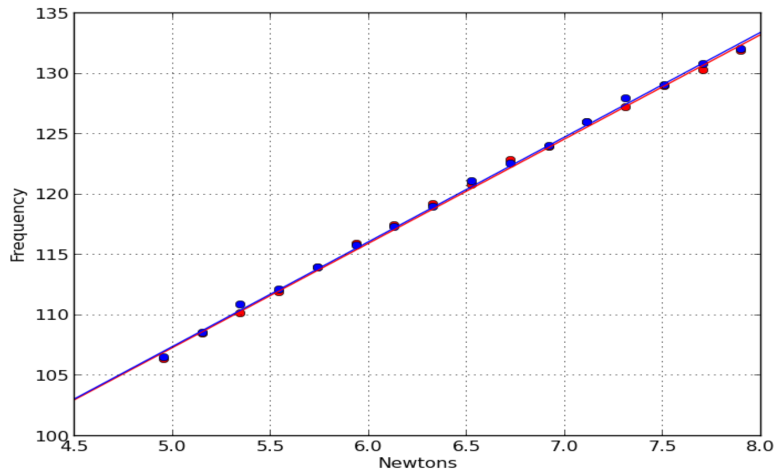

Figure 14: Frequency vs. Tension long straw

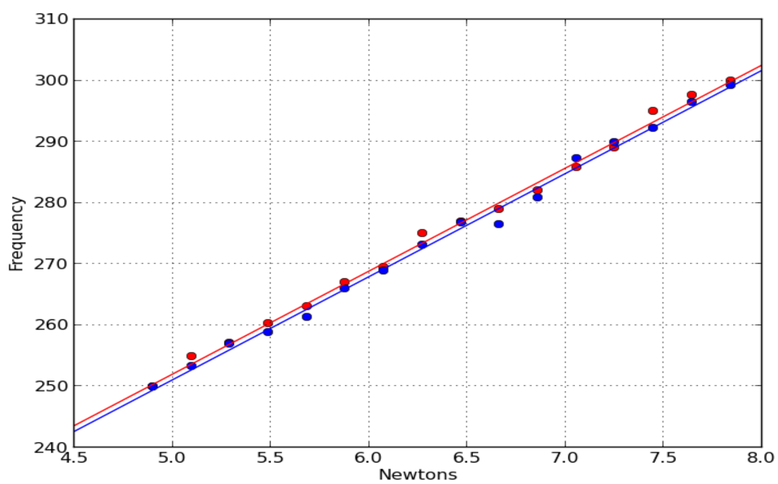

Figure 15: Frequency vs. Tension short straw

6 Conclusion

I was able to successfully find a relationship between the tension, frequency, and length of the straw. This study should be continued to see if the frequency offset remains constant or changes for varying lengths of straws and to acquire a proper humidity test.

7 References

Mu2e Conceptual Design Report. Batavia: Fermi National Accelerator Laboratory, 2012.